Department of Veterans Affairs

Journal of Rehabilitation Research and Development Vol. 37 No. 5, September/October 2000
Pages 511–515

Thermal response of skin to cyclic pressure and pressure with shear: A technical note

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Abstract—The thermal response of skin to pressure alone and to pressure with shear was compared under cyclic loading conditions. Stresses were applied to the anterior aspect of the leg of three healthy subjects for time intervals up to 10 min, and the difference in temperature between the stressed site and a contralateral control site was assessed after load release. The thermal recovery time (TRT), the time interval between load release and either a maximum or a stabilization in the temperature difference vs. time record was determined. Results demonstrated that for a resultant stress of 142.9 kPa, TRTs were longer for combined pressure and shear than for pressure alone. For Subjects A, B, and C, TRT increases were 1.5 min, 5.5 min, and 2.0 min respectively. For a resultant stress magnitude of 71.4 kPa, increases were 1.5 min, 3.5 min, and −0.5 min respectively. Comparing responses for different resultant stress magnitudes for pressure-only application, TRTs were 1.5 min, 1.5 min, and 5.5 min longer for the 142.9-kPa condition than for the 71.4-kPa condition for Subjects A, B, and C. For combined pressure and shear, increases were 1.5 min, 3.5 min, and 8.0 min respectively. A next step will be to determine if the TRT differences measured here are physiologically relevant and have clinical meaning. The thermal response assessment method could then potentially be used to quantitatively evaluate the effects of different interface design features in lower-limb prosthetics on tissue response.

This material is based upon work supported by the National Center for Medical Rehabilitation Research (NCMRR) at the National Institute of Child and Human Development (NICHD).

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Key words: *blood flow, pressure, prosthetics, shear, skin, thermal recovery.*

INTRODUCTION

Although interface pressure and shear combinations can be controlled by a prosthetist through socket design and fitting decisions (e.g., socket shape, liner material, alignment, componentry), it is not clear which pressure/shear combinations are acceptable, which are skin threatening, and on what patient characteristics response depends. This lack of information limits fitting effectiveness, and it may be part of the reason for frequent occurrence of infection or skin breakdown in prosthesis users (reported as 38 percent in one study [1]). An important part of the problem is that a means to quantify susceptibility of skin injury to pressure and shear is not available.

On a population of nursing home patients, Meijer (2) used a thermal response assessment method (3) to show that thermal recovery time (TRT) to pressure application correlated with the risk of developing pressure ulcers. After a 10-min statically applied pressure was released, the time for the temperature difference between the stressed site and an unstressed site 10 to 15 cm away to reach either a maximum or a constant value was assessed. Results demonstrated that TRT correlated significantly with the risk of developing pressure ulcers, with risk defined using data on ulceration occurrence over a 1-

month follow-up period for the 109-person subject population used. Thus the developed assessment method is useful to the clinical evaluation and treatment of bedridden and wheelchair-bound patients.

A thermal recovery assessment method possibly could be used to evaluate skin response under conditions of relevance to lower-limb prosthetics, using different cyclically applied pressure/shear combinations. For such a method to be demonstrated effective for this purpose, however, two questions must be answered: (1) Do different stresses cause different TRTs? (2) Are the differences physiologically relevant, and do they have clinical meaning? The purpose of this Technical Note is to present preliminary data to address question (1). If encouraging results were demonstrated, a base from which to pursue question (2) would be established.

METHODS

Subjects

Three male subjects participated in this study. Subject A was Caucasian and 24 years of age; Subject B was Caucasian and 26 years of age; Subject C was Indian and 40 years of age. None were tobacco smokers. All subjects were in good health and had no skin abnormalities on their lower limbs at the time of the study. Institutional human subjects' approval was obtained for all procedures.

Instrumentation

To apply mechanical stress to the skin, a custom-designed closed-loop biaxial force controller was used (4). The device applied user-specified normal and shear force wave forms to the anterior aspect of the leg while the subject was seated with legs supported. The wave forms used in this study were double-peaked curves (**Figure 1**; ~1 Hz) taken from interface stress measurements on a transtibial amputee subject ambulating with a prosthetic limb (5). A 7 mm × 8 mm Pelite pad of 3-mm thickness contacted the skin surface. The Pelite foam was rounded at the edges to help achieve a uniform stress distribution on the pad surface. It is assumed in calculation of applied stresses that the normal and shear forces were uniformly distributed on the bottom of the Pelite pad. There was no slip between the pad and skin when pressure and shear stress were applied. Though stress was expected to be reasonably well distributed on the pad surface, such was not necessarily the case for stresses deeper into the skin tissues near the underlying bone. No estimates can be drawn of those stress distributions from the data measured here.

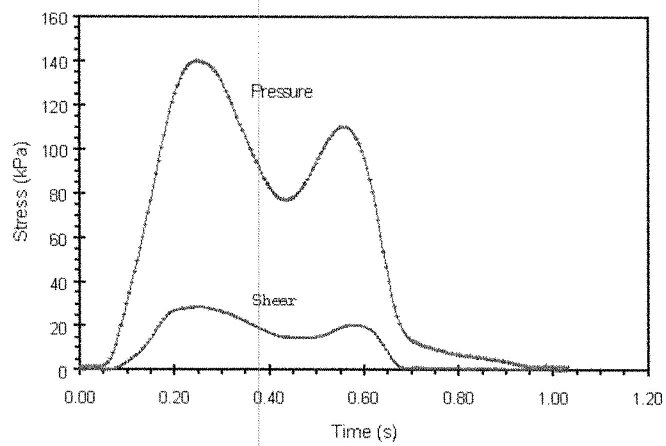


Figure 1.
Shapes of applied wave forms. Cyclic pressure and shear stress were applied. One loading cycle is shown.

To assess thermal response, an infrared temperature sensor (Dermatemp, EMG Associates, Stamford, CT) with a resolution of 0.1°C and a sensing area of 7.9 mm^2 was used. The use of a non-contacting sensor as opposed to a contacting sensor ensured that the thermal conductivity of the measurement device did not alter the response of interest.

Because the measurement from the temperature sensor was sensitive to changes in distance from and angular orientation to the skin surface, the ends of four cotton swabs were affixed to the end of the sensor and used as reference guides to position the sensor consistently. The ends of the swabs formed a 22.2 mm × 22.2 mm square grid around the 7.9 mm^2 sensing area. The swabs lightly contacted the skin surface during measurement. Evaluation using a water bath at a controlled temperature demonstrated this method effective to eliminate temperature measurement variability from inconsistent positioning.

Study Protocol

To prepare for a session, skin on the anterior aspects of the proximal halves of the legs was cleaned with soap and water and shaved. After drying the skin, the subject was allowed to sit comfortably for at least 15 min. The load applicator was positioned on one of the tibial flares between the tibial condyles and the midpoint of the tibia (**Figure 2**). One of four loading conditions was applied:

(1) high pressure only: 142.9-kPa pressure, 0-kPa shear stress; (2) high pressure and shear: 140.0-kPa pressure, 28.6-kPa shear stress; (3) low pressure only: 71.4-kPa pressure, 0-kPa shear stress; and (4) low pressure and shear: 70.0-kPa pressure, 14.2-kPa shear stress. Conditions (1) and (2) were of the same resultant stress (142.9 kPa), and conditions (3) and (4) were of the same resultant stress (71.4 kPa). Ordering of loading sessions was set to be random. For all cases the minimum pressure in the cyclically applied wave form was 1.8 kPa (**Figure 1**), while the minimum shear was 0 kPa. The 1.8-kPa lower bound mimics the clinical application of interest: stresses on a residual limb during ambulation with a prosthesis where contact with the prosthetic socket is maintained during the swing phase of gait. The 1.8-kPa level is less than the 8-kPa threshold shown to cause blood flow occlusion in human skin (6). The loading durations were 10 min for Subjects A and B, and 5 min for Subject C. Because only differences in results within a subject were of interest in this preliminary investigation, variability in the duration of the applied load between subjects was considered acceptable.

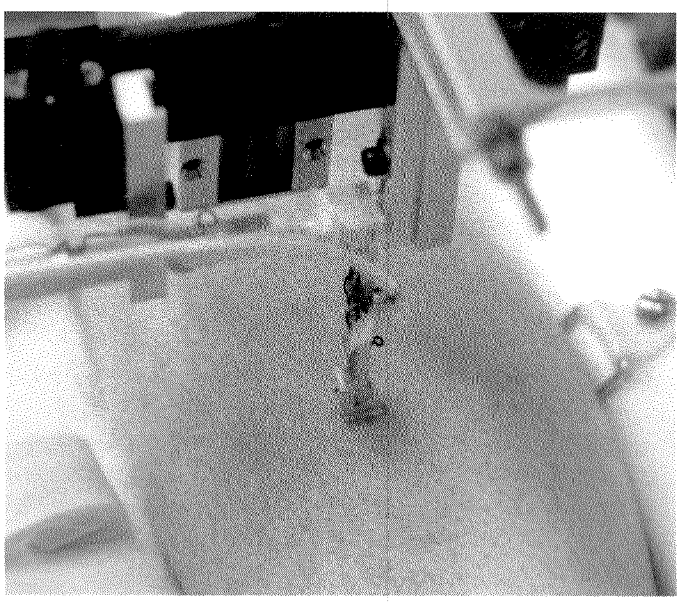


Figure 2.
Load applicator. The device applies cyclic pressure and shear stress to the anterior aspect of the leg.

After loading, the load applicator device was quickly removed and the skin temperature at the stressed and contralateral control sites assessed. Temperature measurements were taken at 30-s intervals at both sites until a non-increasing temperature difference between the stressed and contralateral control sites was maintained.

Analysis

The difference in temperature between the stressed site and the contralateral control site was determined for each trial. The TRT was defined as the time interval between load release and either a maximum or a stabilization in the temperature difference vs. time record. Stabilization was defined as a period of at least 4 min over which the temperature did not increase. The 4-min interval was arbitrary. Selection of a longer interval did not appreciably change the qualitative relationships in the data (presented below). However, it did tend to increase the TRTs, because a lower slope threshold for recovery was specified. Due to the resolution limit of the instrument, a lower slope threshold would have increased error in the analysis.

RESULTS

There were two general patterns of recovery: a gradual increase to a constant value (a in **Figure 3**), and an increase to a maximum followed by a slow decrease to a constant value (b in **Figure 3**). Either response was often preceded by a short interval immediately of constant or decreasing temperature difference immediately after load release (c in **Figure 3**).

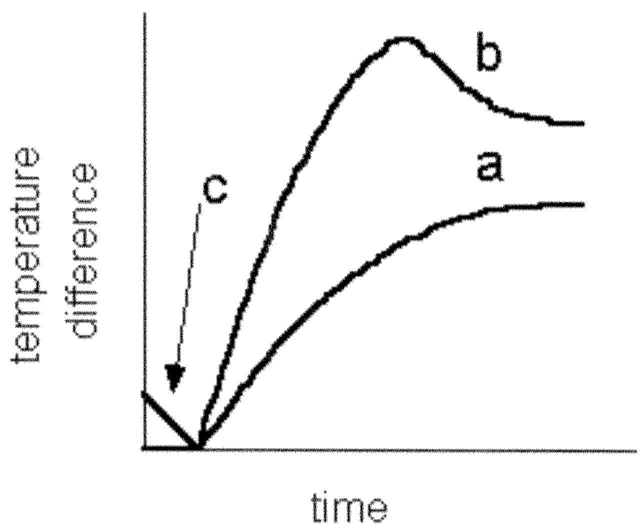
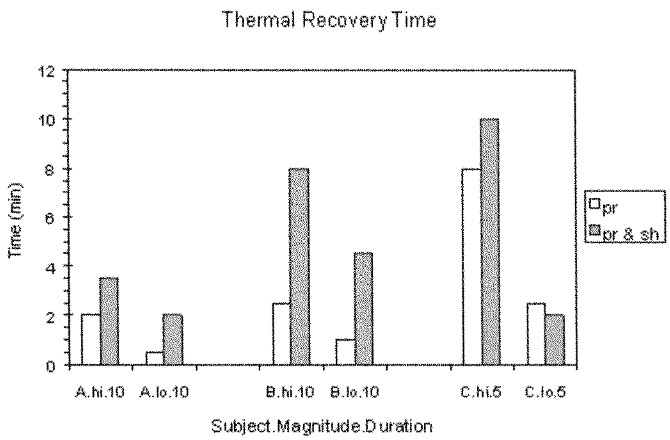


Figure 3.
Thermal response curves after load release. Two patterns were apparent: a gradual increase to a constant value (a), and an increase to a maximum followed by a slow decrease to a constant value (b). In some cases a short period of constant or decreasing temperature difference occurred immediately after load release (c).

For the high-load condition (142.9 kPa), all subjects demonstrated a longer TRT for the combined pressure and shear configuration than for the pressure-only configuration (**Figure 4a**). The differences were 1.5 min, 5.5 min, and 2.0 min for Subjects A, B, and C respectively. This trend was consistent for the low-load condition (71.4 kPa) for Subjects A and B but not for Subject C. Differences were 1.5 min, 3.5 min, and −0.5 min respectively.



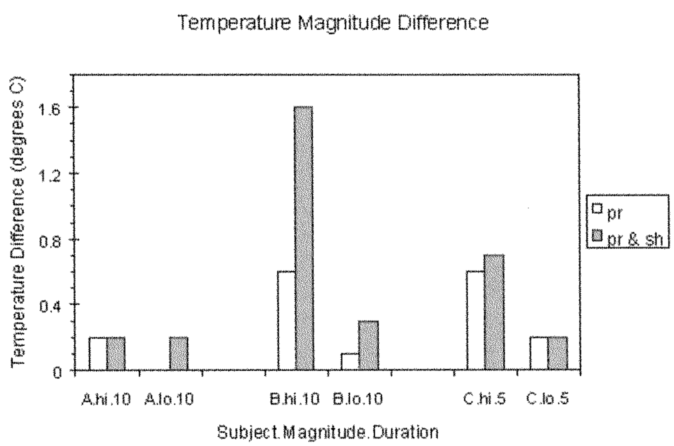


Figure 4.
Thermal response to stress for three subjects (A, B, C). **a:** Thermal recovery times for pressure alone and for combined pressure and shear for high (142.9 kPa) and low (71.4 kPa) resultant stress magnitudes are shown. Loading durations of 5 and 10 min were used. **b:** Temperature differences after load release are shown for the three subjects.

TRTs were longer for loads of greater stress magnitude. For pressure-only application, TRTs were 1.5 min, 1.5 min, and 5.5 min longer for the 142.9-kPa resultant stress case than for the 71.4-kPa resultant stress case for Subjects A, B, and C respectively. For combined pressure and shear, increases were 1.5 min, 3.5 min, and 8.0 min respectively.

Interestingly, the magnitudes of maximum temperature difference from immediately after load release to the maxima or stabilization point did not show trends entirely consistent with the TRT data (**Figure 4b**). In two cases (A.hi.10, C.lo.5), the magnitudes for pressure only and for combined pressure and shear were the same. Except for the combined pressure and shear data for Subject A, all tests demonstrated higher magnitude temperature differences for the high-load configurations than for the low-load configurations.

DISCUSSION

Results from this preliminary study demonstrate that different stresses cause different TRTs. Conditions with increased shear:pressure ratios and higher resultant stress magnitudes resulted in longer TRTs.

The atypical TRT result, comparable recovery times between pressure alone and combined pressure and shear for the low-load configuration for Subject C, could be due to the short load application period (5 min, instead of 10 min as for Subjects A and B) or the resolution limits of the temperature measurement device. The slopes of the recovery curves were low. A device with a higher resolution would be needed to evaluate this possible limitation.

Increases in temperature magnitude difference for combined pressure and shear vs. pressure alone and for high vs. low stress were demonstrated in some, but not all cases. However, in a study in which stresses of greater magnitude were applied under static loading conditions, temperature increases after load release were well correlated with the magnitude of the applied load (7). Thus temperature magnitude difference, unlike TRT, might be an effective discriminator of different interface loads only at relatively high magnitude stress levels.

A next step in this research effort will be to determine the physiologic source of the TRT differences and their clinical relevance. In Meijer's study in which static loading was applied, the thermal response after load release was attributed to a transient blood flow response (3). In the study presented here, however, cyclic loading as opposed to static loading was studied, and all subjects were relatively young and healthy individuals. During 31 percent of each load cycle, stresses were less than the 8 kPa required for blood flow occlusion (6). Thus it is possible that reperfusion occurred. The TRTs here were relatively short (from 0.5 min to 10.0 min in duration), possibly because of reperfusion, compared with Meijer's study in which TRTs of 25 min to 45 min were measured in problem subjects. It is still possible that a transient blood flow response is occurring here, and that curve b in **Figure 3** is indicative of reactive hyperemia. However, it remains to be demonstrated that a longer TRT is more detrimental than a shorter one and that a longer TRT indicates a greater susceptibility to skin breakdown if the loading condition was continued. Identification of the source of the TRT differences and evaluation of their clinical relevance is thus an appropriate next step in this research. If clinical relevance were demonstrated, then TRT measurement potentially could be used to quantitatively evaluate the effects of different interface design features in lower-limb prosthetics on tissue response.

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Submitted for publication March 1, 2000. Accepted in revised form April 20, 2000